Modal energy also includes energy used in gaining access to or from line-haul travel. The estimates shown in Table 3 do not include access energy, for lack of data. This introduces serious distortion for some modes. Most important, the inland barge industry often draws traffic over a distance of 200 or 300 miles from a navigable waterway. This has been particularly true in recent years as both the Rock Island and the Chicago, Milwaukee, St. Paul and Pacific railroads have deteriorated, forcing many farmers to truck their grain to the river. If truck access accounts for as much as one-third of the total movement by barge, it is enough to reduce average barge energy efficiency to roughly that of rail. This may also increase the circuity component for barge movement. On the other hand, the fact that most barge grain movements are downstream, where barge is a very efficient hauler, works to counteract some of these effects. Access energy requirements are also likely to be important for rail TOFC and air freight, and to a lesser extent for truck.

Rail vs. Truck. The rail mode is thought by some to have a four-to-one edge over the truck mode in energy efficiency. Table 3 shows that while rail is clearly more energy-efficient than truck, its lead is about two-to-one overall (1,720 BTUs per net ton-mile versus 3,420 for truck) and closer to 1.7-to-one for TOFC, which competes most directly with truck. This difference between modes varies considerably from commodity to commodity. For certain bulk commodities--coal, for example--rail may be as much as six times as efficient as truck, while for certain types of manufactured goods--such as electrical machinery--there is very little difference between the modes. 2/

Rail vs. Barge. Overall, the inland barge is a more energy-efficient mode than rail. The typical coal unit train appears, however, to be more energy-efficient than overall barge transport (but less efficient than downstream barge transport). For other bulk commodities the relative energy efficiency depends greatly on the commodity and the direction of movement. Since most petroleum products, for example, travel in an upstream direction, movement by rail is probably more energy-efficient for them. Grain, on the other hand, is more likely to travel downstream, and thus would use less energy on barges. If a commodity has to be transported a significant distance to or from the waterway, this may offset the advantage of barges.

2/ Axel Rose, Energy Intensity and Related Parameters of Selected Transportation Modes: Freight Movements, Oak Ridge National Laboratories (June 1979). See Tables 5.11 and 6.5 for estimated commodity breakdowns.

Air vs. Truck. Freight transport in the belly of passenger planes is only about 15 percent more energy-intensive than truck traffic, even though service quality is higher. The space available for belly freight is quite limited, however, although increased use of wide-body planes should make more belly space available. All-cargo planes are the least energy-efficient mode of transport, requiring more than eight times as much energy as trucks. The difference would probably appear even greater if data on access energy were available, since most metropolitan areas have many truck terminals but rarely more than one air freight terminal.

SHORT-TERM VERSUS LONG-TERM ENERGY USE

In any discussion of alternative energy policies, it is important to distinguish between the short term and the long term. Short-term comparisons of energy efficiency need not give much weight to the costs of constructing new guideways for vehicles. This is particularly true for a country such as the United States with a well-developed transportation infrastructure. Thus, any analysis of the likely short-term energy effects of a particular policy change should exclude construction energy. Table 4 adjusts the modal energy estimate in Table 3 to exclude construction energy. Also shown in Table 4 is the energy required for propulsion and the related effects of circuity--excluding all the "overhead" energy of vehicle manufacturing, guideway construction, and maintenance. Except for oil and coal slurry pipeline, almost all the energy used for propulsion and circuity is derived from petroleum.

Clearly, there are potential energy savings from switching traffic from one mode to a more efficient one—as, for example, from air to truck or from rail to barge. Table 5 shows the hypothetical savings if 10 percent of the traffic currently carried by each mode were switched to the next most efficient mode. Changes of this magnitude are unlikely to occur without drastic changes in current policy. In any case, the potential savings are modest, equal to a total of 68,000 barrels of oil per day at a time when U.S. energy consumption totals 36 million barrels per day.

CONCLUSIONS

Of the major modes of domestic freight transportation, oil pipelines are, on average, the most energy-efficient, followed by barges, coal slurry pipelines, railroads, trucks, and air freight. Such generalizations can be misleading, however, since they conceal wide variations among commodities hauled, levels of service offered, and specific geographic circumstances.

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TABLE 4. ESTIMATES OF ENERGY USE OVER THE SHORT TERM FOR SIX MODES OF FREIGHT TRANSPORTATION (In BTUs per net ton-mile)

Mode	Propulsion Energy and Circuity Alone a/	Modal Energy Excluding Construction Energy
Rail - Overall	1,000	1,410
TOFC	1,440	1,760
Unit coal train	560	740
Truck		
Average intercity	2,560	3,050
Barge - Overall	770	900
Upstream	1,060	1,190
Downstream	400	530
Air		
All-cargo plane	27,560	28,510
Belly freight	3,750	3,870
Oil Pipeline	360	470
Coal Slurry Pipeline	1,100	1,220

a/ Excludes energy used for vehicle manufacture, guideway construction, and maintenance.

For example, oil pipelines and coal slurry pipelines are both specialized modes of transportation, each designed to move only one commodity. The relative efficiency of oil pipelines is useful in analyzing alternative ways of moving petroleum (barges and tankers, for example), but has little relevance for freight transportation in general. Similarly, while barges, on average, are more energy-efficient than railroads, the gap narrows when comparison is restricted to the bulk commodities that barges carry almost exclusively. Coal unit trains, for example, are roughly comparable to barges in energy efficiency.

TABLE 5. POTENTIAL ENERGY SAVINGS FROM SWITCHING FREIGHT TRAFFIC TO MORE EFFICIENT MODES

		Savings From Switching 10 Percent of Traffic to Next Most Efficient Mode	
Mode	1980 Intercity Traffic (In billions of ton-miles) a/	Total Savings (In thousands of barrels of oil equivalent per day)	Savings per Ton-Mile (In BTUs) b/
Oil Pipeline	575	N/A	N/A
Barge c/	307	6	430
Rail	921	22	510
Truck d/	565	34	1,290
Air e/	5	6	25,460

N/A = Not Applicable.

a/ Transportation Association of America.

b/ Based on estimates in Table 4.

c/ Traffic on rivers and canals. Excludes 113 billion ton-miles of domestic freight on the Great Lakes.

d/ Assumed to switch to TOFC.

e/ Assumed to switch from all-cargo plane.

This analysis should provide a useful basis for weighing alternative national policies in the field of transportation. It should also be applicable to more limited problems. For example, the effects of railroad deregulation on energy use could be estimated in terms of reduced circuity, changes in average load, and the amount of traffic attracted from other modes. To estimate the energy effects of a specific project such as the Tennessee-Tombigbee Waterway, however, would require modification of the energy estimates in this report.

APPENDIXES

APPENDIX A. DESCRIPTION OF INPUT DATA

This appendix describes the data used in estimating the basic components of energy use given in Chapter III. Each component--propulsion energy, vehicle manufacturing energy, guideway construction energy, maintenance energy, access energy, and circuity--is discussed separately, and typical or representative values are selected for each mode of transportation. These are used in Chapter III to calculate the measures of overall energy efficiency for each mode.

PROPULSION ENERGY

Propulsion energy is the most important single component of energy consumption. It represents between 40 percent (for barges and railroads) and 90 percent (for air cargo) of the total energy required to transport goods.

Railroads

The average amount of energy used in rail propulsion varies widely. It is lowest for unit trains with 100 or more similar, heavily loaded cars on an uninterrupted long-distance journey. It is highest for TOFC (trailer-on-flatcar) trains carrying lower-density cargos, usually manufactured goods, for shorter distances at much higher speeds and on shorter trains. Between these two extremes is the more typical general-purpose train consisting of boxcars, hopper cars, or gondolas.

Table A-1 summarizes recent estimates of railroad freight propulsion energy use in terms of BTUs per ton-mile of cargo. The first group of estimates show averages for all rail freight in either the United States or Canada for recent years. The U. S. figures are all based on data submitted to the Interstate Commerce Commission (ICC) by U. S. Class I railroads (those with annual revenues greater than $50 million). Since they all derive from the same source, there is very little difference among most of the estimates, which range between 630 and 690 BTUs per ton-mile of cargo. They have not changed much in recent years, the average fluctuating

TABLE A-1. ESTIMATES OF PROPULSION ENERGY REQUIREMENTS FOR RAILROADS

Source a/	BTUs Per Ton-Mile b/	Comments
Rose	630	Per revenue ton-mile, 1979 preliminary estimate
	670	Per revenue ton-mile, 1977, ICC data
	274	Per gross ton-mile, 1977, ICC data
Pollard	664	1977
Leilich	687	1972
CACI	594	Estimated for 1975
DelCan	548	1976, Canada
IBI Group	1,200	General freight, Canada
	500	Bulk commodities, Canada
	289	Per gross ton-mile, 1975 actual for Canada
USRA	262	Conrail, 1977, per gross ton-mile
	594	Conrail, 1977, all traffic
	319	Conrail, 1977, unit trains
	1,272	Conrail, 1977, TOFC
	470	Conrail, 1977, local service
	613	Conrail, 1977, road service
Sebald	515	1971, area served by Mississippi River and Gulf Intracoastal Waterway

(Continued)

TABLE A-1. (Continued)

Source a/	BTUs Per Ton-Mile b/	Comments
Office of Technology Assessment	390	Weighted average for four proposed coal unit trains, range = 340-580
Western Railroad Association	222	Coal unit train
Zucchetto	400	Coal unit train from Colstrip, Wyoming to St. Paul, Minnesota
Reebie Associates	1,205	Portland-Los Angeles, door-to-door, 1971
	1,723	TOFC; Portland-Los Angeles, door-to-door, 1971
	1,358-2,905	Advanced TOFC, Portland-Los Angeles, door-to-door
Iowa DOT	1,500	10 car train, ½ TOFC, 50 mph, no grade
	4,100	10 car train, ½ TOFC, 50 mph, 1 percent grade

a/ See Appendix B for full citation of each source.

b/ Per ton-mile of cargo unless stated otherwise. Gross ton-miles include the weight of cars and locomotives, and empty backhauls.

between 630 and 710 BTUs per net ton-mile. 1/ ICC data show about 275 BTUs per gross ton-mile (including the weight of cars and locomotives). The two Canadian estimates are similar to those for the United States.

A comparison of energy used per gross ton-mile and ton-mile of cargo indicates that only about 40 percent of the load moved by railroads is actual cargo, the remaining 60 percent representing dead weight due to empty backhauls and the weight of the freight cars and locomotives themselves. Some railroads are experimenting with lighter equipment and new designs. For example, the Santa Fe claims that its lightweight "Ten Pack" TOFC cars reduce energy use by 10 percent. The Bi-Modal (railroad/highway) car developed by Reebie Associates promises even greater energy savings.

Empty backhauls are a very significant factor in reducing the inherent efficiency of railroads. (Wind resistance both on the locomotive and between cars is also important, particularly for TOFC and COFC.) The ICC estimates that, on average, a rail car travels 79 miles empty for every 100 miles it travels with a load (an empty/loaded ratio of 0.79). 2/ There is some variation around this average, and certain specialized types of cars travel more miles empty than full--covered hopper cars and tank cars, for example. Since the typical rail car weighs between 60,000 and 65,000 pounds, considerable energy is required just to move an empty car. Some of these empty car miles represent inefficient use of resources, while others merely reflect the inherent characteristics of the railroad business. For example, most unit trains (devoted to hauling a particular commodity such as coal, usually between the same origin and destination), travel as many miles empty as they do loaded. Empty backhauls are a striking illustration of the difference between technical efficiency and practical efficiency.

The lower part of Table A-1 contains estimates of propulsion energy for specific railroads, regions, or types of movement. These indicate the considerable variability underlying the modal averages shown in the upper

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1/ Axel B. Rose, Energy Intensity and Related Parameters of Selected Transportation Modes: Freight Movements, Oak Ridge National Laboratory for U.S. Department of Energy, Office of Conservation and Solar Applications (June 1979), pp. 5-12. Rose, in a personal communication, reports the 630 BTU figure as a preliminary estimate for 1979.

2/ Interstate Commerce Commission, Bureau of Accounts, Ratio of Empty to Loaded Freight Car-Miles by Type of Car and Performance Factors for Way, Through and All Trains Combined - 1972 (December 1973), Statement No. 1S2-72, p. 10.

part of the table. For example, Conrail's overall energy efficiency per ton-mile of cargo is estimated to be somewhat higher than the rail industry average (594 BTUs as against 670 BTUs) although there is little difference per gross ton-mile (262 BTUs as against 274 BTUs). The several estimates of energy requirements for unit coal trains are all significantly less than the average for all traffic (222-400 BTUs versus 630-670 BTUs). In contrast, the estimates for TOFC traffic are substantially greater than the overall average. The estimates prepared by Reebie Associates for traffic between Portland and Los Angeles include access energy--the energy used in moving the cargo to and from the railroad—and are thus not fully comparable with the other estimates in the table.

Most of the rail propulsion energy estimates in Table A-1 are based on aggregate data, or on engineering projections. None are measurements of actual fuel use under controlled conditions. Such controlled experiments are difficult to perform, since measurement of locomotive fuel use requires either cumbersome before-and-after comparisons of the fuel consumed or the installation of a temporary fuel gauge. Moreover, freight cars are often added to or removed from a train at intermediate points, making it difficult to estimate the actual load carried.

In recent years, some railroads have made field tests of fuel use under operating conditions. Table A-2 summarizes a number of the results. Two general conclusions are apparent.

First, except for branch-line operations as measured by the Missouri Pacific Railroad (see the first line of Table A-2), energy use increases with the speed and quality of service provided. High-speed, high-priority TOFC and COFC trains require significantly more energy per ton-mile of cargo than does the typical freight (boxcar) train, which in turn requires significantly more energy per ton-mile of cargo than do trains carrying bulk commodities, such as coal unit trains. These results appear to confirm the more aggregative estimates presented in Table A-1. With one or two exceptions, most of the boxcar and mixed freight trains are close to the average for rail freight as a whole (650-700 BTUs per ton-mile of cargo). TOFC service tends to be 50 percent or more above this while coal unit trains are about half the average--both of these results being in line with the estimates of Table A-1.

Second, the energy required per ton-mile of cargo increases directly with the horsepower per gross ton-mile. The extra horsepower is needed to provide high-speed service for higher-value movements such as with TOFC or COFC. At the other extreme, unit trains hauling bulk commodities

TABLE A-2. FIELD MEASUREMENTS OF RAIL FREIGHT PROPULSION ENERGY USE

Railroad	Car Type	BTUs per Gross Trailing Ton-Mile	BTUs per Ton-Mile of Cargo	Number of Cars per Train	Horsepower per Gross Trailing Ton	Train-Miles in Sample
Missouri Pacific-1974 a/	Box	510	1,445	10	8.6	964
Burlington Northern-1975 b/	TOFC	326	895	27	6.0	19,528
Burlington Northern-1976 c/	Mixed	314	644	44	4.2	9,220
Southern Pacific-1975 d/	Box	145	309	125	0.9	1,148
	TOFC	232	766	39	2.6	574
	Mixed	206	672	76	1.5	574
Santa Fe-1976 e/	TOFC	316	1,372	56	3.7	6,853
	Box	281	709	63	3.2	1,747
	Mixed	234	638	69	3.2	1,604
Illinois Central Gulf-1976	TOFC f/	400	970	32	5.4	3,222
	Box g/	198	521	108	1.6	1,945
	COFC h/	255	731	72	2.6	1,052
	Mixed	314	917	82	3.0	405
Union Pacific i/	TOFC	423	1,012	41	5.7	3,038
Burlington Northern j/	Coal Unit Train	158	256	111	0.8 l/	1,264
Boston and Maine k/	Coal Unit Train	254	412	91	1.0 l/	414
Canadian National-1974 m/	Box	189	329	92	1.2	6,666

(Continued)

TABLE A-2. (Continued)

Railroad	Car Type	BTUs per Gross Trailing Ton-Mile	BTUs per Ton-Mile of Cargo	Number of Cars per Train	Horse-power per Gross Trailing Ton	Train-Miles in Sample
Milwaukee Road						
1979 n/	TOFC	295	850	23	N/A	2,472

SOURCE: All except last two lines, Hopkins and Newfell, Railroads and the Environment: Estimation of Fuel Consumption in Rail Transportation, vol. II, U.S. Department of Transportation, Transportation Systems Center (September 1977).

a/ Six round trips over 87-mile branch line in Arkansas and Louisiana.

b/ Runs between Chicago and Seattle, 2,179 total miles broken into two segments at Minot, North Dakota. Two-thirds of measurements were for Chicago-Minot segment.

c/ Ten trips between Chicago and Minot, N. D.

d/ A total of eight trains over 287-mile route in Central Valley of California.

e/ Three round trips between Kansas City and Los Angeles or Barstow, California.

f/ Two round trips between Chicago and New Orleans.

g/ Round trip between Chicago and New Orleans plus two short segments.

h/ Round trip between Chicago and Council Bluffs, Iowa.

i/ Round trip between North Platte, Neb., and Los Angeles.

j/ Round trip from Lincoln, Neb. to Metropolis, Ill.; net vertical drop of 700 feet.

k/ Round trip from Mechanicsville, N. Y. to Bow, N. H.

l/ Horsepower per gross trailing weight ratio refers to loaded portion of trip only.

m/ Ten round trips between Montreal and Toronto. Source: DelCan, "A Comparison of Modal Energy Consumption in Intercity Freight."

n/ Six trips of Sprint TOFC train between Chicago and Minneapolis/St. Paul. Includes operations in railroad TOFC terminal. Source: Department of Energy.

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require reliability of service more than high speed, make few if any intermediate stops, and typically carry much greater tonnage relative to their horsepower than do other trains.

Intercity Trucks

Truck freight service is of two broad types: intercity and local pick-up and delivery. Intercity service is typically in large (up to 80,000 pounds gross weight) combination trucks with one or more trailers pulled by a tractor. After the intercity truck delivers its cargo to a terminal, smaller delivery trucks may take it to its ultimate destination. In terms of ton-miles of cargo, the large intercity trucks are usually more energy-efficient than the smaller delivery trucks. This paper considers only intercity truck transportation. 3/

Intercity truck transport, in turn, is of two types: truckload (TL) and less-than-truckload (LTL). Truckload service is used mostly by larger shippers in regular service. It is more energy-efficient on a ton-mile basis than less-than-truckload service.

Table A-3 summarizes recent estimates of truck freight propulsion energy use. Those in the top part represent averages for all intercity truck freight in either the United States or Canada. In contrast to the estimates for railroads, there is greater variation among these estimates--which range between 1,800 and 2,500 BTUs per ton-mile of cargo.

Most of these estimates use two sets of data: the average load and the average miles per gallon for a certain type of truck. The ICC collects data on average load, but there is no consistent source of data on truck fuel economy. Thus, there is greater uncertainty associated with each particular estimate than is the case for railroads. Further uncertainty is caused by the existence of many different types of trucks. For example, the Transportation Systems Center estimate in Table A-3 is for combination trucks, of which the Class VIII diesel trucks (over 30,000 pounds gross weight) considered by Rose are a subset.

3/ The exclusion of urban freight transportation presents a somewhat optimistic view of truck energy use. Of course, other modes (notably railroads and air freight) depend on local truck service for pick-up and delivery and are thus also affected by this exclusion.

As with other modes of transportation, extra energy is consumed in empty backhauls. These are included in most of the estimates in Table A-3. The ICC estimates that in 1976 some 20.4 percent of trucks operated empty and an additional 14.4 percent were only partially loaded. In total, 27.1 percent of the available truck capacity was empty. 4/ For trucks engaged in interstate service the estimates are slightly lower, while for trucks that are unregulated by the ICC the estimates are higher. The comparable estimate by the ICC for railroads is 44 percent. 5/ Adjusting some of the estimates in Table A-3 for the effect of empty backhauls is not easy. For example, Rose estimates that a Class VIII truck (the largest truck class, typically used for long-haul service) achieves about 4.5 miles per gallon when loaded. 6/ At an average load of 18.04 tons, this yields about 1,710 BTUs per ton-mile. Rose adjusts this for the percent of truck capacity that is empty (using a 1974 estimate by the Department of Transportation of 30.7 percent empty, rather than the estimate for 1976 by the ICC of 27.1 percent), arriving at an overall estimate of 2,470 BTUs per ton-mile of cargo. This estimate should be adjusted, however, for the greater fuel economy achieved when a truck is empty. 7/

4/ Interstate Commerce Commission, Bureau of Economics, Empty/Loaded Truck Miles on Interstate Highways During 1976 (April 1977). This includes all trucks whether or not they are regulated by the ICC.

5/ This number is different from that used in the rail section above since the ICC presents its rail survey in terms of the ratio between empty miles and loaded miles. The resulting rail ratio, 0.79, is equivalent to the figure of 44 percent empty mentioned here (79/179).

6/ Rose, op. cit., pp. 6-10.

7/ This fuel economy can be estimated using an engineering relationship such as Smith's formula for resistance (G.L. Smith, Commercial Vehicle Performance and Fuel Economy, SAE SP-355, Warrendale, Pa., 1970):

$$R_t = (W_e + W_c)\ (a + bV)\ S + c\,DAV^2$$

where

R_t = total resistance to straight-line movement over level terrain (lbs)

TABLE A-3. ESTIMATES OF PROPULSION ENERGY REQUIREMENTS FOR INTERCITY TRUCKS

Source a/	BTUs per Ton-Mile b/	Comments
Rose	2,470	Class VIII diesel trucks at 4.5 mpg and average load (2,140 if adjusted for higher mpg when empty)
	1,860-4,120	Depends on commodity carried
Pollard	2,530	1977, combination trucks only (5.42 mpg)
Leilich	2,343	1972
AAR Factbook	1,980	1978, regulated common carriers
CACI	2,403	1975, estimated
DelCan	1,900	1976, Canada, estimate
IBI Group	2,100-3,400	Canada, depends on weight of cargo (5-5.5 mpg)
Paxson	2,170	15-ton load; intercity TL service
	1,690	20-ton load; intercity TL service
	1,415	25-ton load; intercity TL service, 6 mpg empty, 4.5-5 mpg loaded, 1977-1979
Department of Energy	1,596	1979, 12 trips between Chicago and Minneapolis/St. Paul, 45-foot trailers
National Highway Traffic Safety Administration	1,207	1979 road test near Frederick, Maryland, over 53 mile course, 72,000 lb. gross vehicle weight
	2,514	48,000 lb. gross vehicle weight

(Continued)

TABLE A-3. (Continued)

Source a/	BTUs per Ton-Mile b/	Comments
Yellow Freight		1976, trip between Baxter Springs, Kansas, and Dallas, 420 miles, with 22 tons of ballast, 10-15 mph wind
	1,560	Bias-ply tires (with headwind)
	1,383	Radial tires (with headwind)
	1,333	Bias-ply tires (with tailwind)
	1,148	Radial tires (with tailwind)
Reebie Associates	1,723	Portland-Los Angeles, twin 27s door-to-door, 1971
Iowa DOT	3,000	10 tons of cargo per truck, 50 mph, no grade
	4,400	10 tons of cargo per truck, 50 mph, 1 percent grade
Jack Faucett Associates (Case Studies)	1,510	1975, bulk commodity, common carrier, 4.6 mpg, 20 tons average load
	2,030-2,190	1975, general freight, common carrier, 4.37-4.71 mpg, 14.5 tons average load
	1,950-2,240	1975, general freight, common carrier, 4.42-5.07 mpg, 14 tons average load
American Trucking Association	1,335	Truck loaded at federal maximum 80,000 lbs. gross vehicle weight

a/ See Appendix B for full citation of each source.

b/ Per ton-mile of cargo unless stated otherwise.

The calculations in footnote 7 indicate that the typical loaded truck that averages 4.5 miles per gallon will average 6.6 miles per gallon when empty. Combining these numbers with the ICC's finding that 27.1 percent of truck-miles are run empty results in an estimate of 2,140 BTUs per ton-mile of cargo as against the 2,470 BTUs used by Rose. Rose's estimate would be correct if, as he apparently assumed, the base estimate of 4.5 miles per gallon were already adjusted for better fuel economy when empty.

The lower part of Table A-3 contains estimates of truck energy use under particular conditions. While the first three of these are based on road tests, only the Department of Energy results represent actual operating conditions. The National Highway Traffic Safety Administration and the Yellow Freight Company tests were not conducted under normal operating conditions, and thus should be interpreted with caution. In particular, the

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7/ (Continued)

W_e = empty vehicle weight (lbs)

W_c = cargo weight (lbs)

a, b = coefficients of tire rolling resistance: $a = 0.0068$, $b = 0.000074$

V = velocity (miles per hour)

S = road surface factor: 1 = normal road

C = coefficient for drag: 0.00253

D = aerodynamic drag coefficient: 0.71

A = vehicle frontal area (square feet)

From this relationship the relative resistance for a loaded truck as against an empty truck can be calculated. With certain additional assumptions (empty weight = 29,000 pounds, loaded weight = 65,000 pounds, velocity = 55 miles per hour, vehicle frontal area = 96 square feet) the resistance of a loaded truck is estimated as about 1.47 times that of an empty truck. This implies that if a loaded truck averages 4.5 miles per gallon, an empty truck should achieve 6.6 miles per gallon.

tests were for trucks with full loads in relatively flat terrain and very little traffic congestion.

The estimate by Reebie Associates 8/ includes energy used in pick-up and delivery. The estimates by the Iowa DOT are based on engineering relationships. They are useful since they show the effect of hills on energy consumption. The last set of estimates represent averages for particular, unnamed trucking companies as reported by Jack Faucett Associates.

Water Transportation

Water transportation in the full sense includes several modes of transportation: towboats pushing barges on inland waterways, tugs and barges on the intracoastal waterways and the Great Lakes, deep-draft vessels on the Great Lakes or in coastal trade, and deep-draft vessels in international commerce. This report focuses on inland barge transportation, but estimates for intracoastal shipping and deep-draft domestic shipping are given here for the sake of comparison.

The estimates in Table A-4 vary considerably, reflecting the generally uneven quality of the data and the difference between the various forms of water transport. In contrast to rail, truck, and air, only about 8 percent of the inland barge industry is regulated by the federal government. Since little information is available on the unregulated sector, data on propulsion energy must be patched together from several sources, including private barge companies, the Interstate Commerce Commission, the U. S. Army Corps of Engineers (for tonnage data), and engineering studies.

Estimates of overall propulsion requirements for the inland waterways range from 272 to 680 BTUs per ton-mile of cargo. Most estimates cluster in the 300-500 BTUs range. Direct comparisons are difficult because of inconsistencies in the underlying data.

Rather than attempt to combine data from several disparate sources, Booz, Allen, and Hamilton selected what they believed to be typical or generic types of vessels: for example, a 1,350 horsepower towboat was selected to represent inland barge movements and then BTUs per ton-mile were calculated on the basis of engineering estimates of fuel economy under

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8/ Reebie Associates, An Improved Truck/Rail Operation: Evaluation of a Selected Corridor, prepared for the Federal Highway Administration (December 1975).

TABLE A-4. ESTIMATES OF PROPULSION ENERGY REQUIREMENTS FOR WATER TRANSPORTATION

Source a/	BTUs per Ton-Mile b/	Comments
Rose	440	1977, all domestic water including inland, lakes, and coastal
Pollard	438	1977, all domestic water modes
	559	1977, inland and local
	376	1977, coastal and lake
Leilich	272	1972, inland
	226	1972, coastal and lake ship
	281	1972, coastal and lake barge
Booz, Allen, Hamilton	481	Inland, based on generic ship (1,350 horsepower)
	380	Coastal average: tug/barge = 355; tanker = 278; other = 941; based on generic vessels
	511	Great Lakes average: dry bulk = 484-543; tanker = 587-652; tug = 304-320 based on generic vessels
CACI	350	1975, estimated for inland
	387	1973, estimated for deep-draft
Sebald	459	1971, Mississippi River and Gulf Intracoastal, does not include all switching energy (adjusted to exclude circuity)
DelCan	932	1976, Canada, shallow and deep-draft

(Continued)

TABLE A-4. (Continued)

Source a/	BTUs per Ton-Mile b/	Comments
Eastman (American Waterways Operators)	352	1977, average for 27 inland barge
Eastman (Water Transport Association)	326	1978, 2 inland barge operators; Lower Mississippi = 278, Ohio River = 329, Illinois River = 366
Zucchetto	249	Dedicated towboat and 15-jumbo-barge tow between St. Louis and St. Paul--data from Federal Barge Lines
Eastman (American Commercial Barge Line)	325	Average for 1978. Range: 264 on lower Mississippi to 605 on Gulf Coast Waterway
Iowa DOT	500	7-barge tow
Hooker and Others	587	1972, coastal tanker for one U.S. firm (Metrics, Inc.)
	638	1975, coastal tanker for one U.S. firm (Metrics, Inc.)
	480	Recalculation of Booz, Allen, and Hamilton estimate of 355 for coastal tanker

a/ See Appendix B for full citation of each source.

b/ Per ton-mile of cargo unless stated otherwise.

typical operating conditions for that vessel. In general, estimates based on such engineering relationships predict lower levels of fuel consumption than those drawn from experience under actual operating conditions. Another study found that the Booz, Allen, Hamilton engineering-based estimates for coastal tankers had to be increased by about one-third in order to match estimates of actual fuel consumption by the industry. 9/

Although all forms of water transport are relatively energy-efficient, at least in terms of propulsion energy, there is considerable variation among the different types of water movement. One study found that two to four times as much energy per ton-mile is required on the Gulf Intracoastal Waterway as on the Lower Mississippi River, because the Lower Mississippi is wider and deeper, has no delays associated with locks or congestion, and typically has larger tows. 10/ Performance on the Lower Mississippi also differs widely from that on other rivers, such as the Ohio. Moreover, typical upstream movement requires about 2.7 times as much energy per ton-mile as does movement downstream. 11/

There have been no controlled measurements of fuel use for barges under actual operating conditions. This is partly because of the difficulty involved in making precise measurements. Several barge lines have reported company-wide averages for their fuel consumption per ton-mile. As given by American Waterways Operators, they average about 350 BTUs per ton-mile of cargo. These results may be somewhat low since they do not appear to include energy used by switch boats.

9/ John Hooker, Axel Rose, and Kenneth Bertram, Comparison of Operational Energy Intensities and Consumption of Pipelines Versus Coastal Tankers: U.S. Gulf Coast to Northeast Coast Routes, U.S. Department of Energy, Office of Transportation Programs (January 1980), p. 10.

10/ R. H. Leilich and others, Energy and Economic Impacts of Projected Freight Transportation Improvements, prepared by Peat, Marwick, Mitchell and Company for Transportation Systems Center (November 1976), pp. 2-29. This analysis is based in large part on a modified version of the Howe formula for Still-Water Speed, p. C-4. The American Commercial Barge Lines reports (in "Modal Productivity Improvement and Related Energy Problems," Traffic Quarterly, April 1980, p. 221) results of 264 BTUs per ton-mile on the Lower Mississippi and 605 BTUs on the Gulf Coast waterway.

11/ Leilich and others, Energy and Economic Impacts.

Air Freight

Air freight is carried either in planes specially designed for the purpose or in the luggage compartments of regular passenger planes. Table A-5 presents estimates of propulsion energy requirements. They vary much more than the findings for other modes, primarily because of differences in method.

TABLE A-5. ESTIMATES OF PROPULSION ENERGY REQUIREMENTS FOR AIR FREIGHT

Source a/	BTUs per Ton-Mile b/	Comments
Rose	3,400	1976, belly freight, incremental energy
	25,360	1976, domestic freight aircraft
	23,310	1976, international freight aircraft
	14,070	1976, average all air freight
Pollard	3,300	1977, belly freight, incremental energy
	25,000	1977, freight aircraft
	11,775	1977, all domestic air freight
	12,409	All air freight
Leilich	14,188	1972, belly cargo, incremental energy
	29,949	1972, belly cargo, average energy
DelCan	45,200	1976, Canada, international and domestic
IBI Group	28,633	Boeing 707, 750-mile trip
Iowa DOT	10,000	Boeing 747, 1,000 miles with 100-ton payload

a/ See Appendix B for full citation of each source.

b/ Per ton-mile of cargo unless stated otherwise.

The calculation of propulsion energy needed for aircraft that carry only freight is straightforward, requiring only data for total fuel consumption and total ton-miles of cargo. A typical estimate is about 25,000 BTUs per ton-mile of cargo.

The calculation of freight energy intensity for aircraft carrying both freight and passengers is more complex. The fuel consumed by the plane must be allocated in some way between freight and passengers. Two approaches have been used. One is to give freight and passengers equal importance, and use a measure such as relative weight to allocate fuel. A typical answer using this approach is about 40,000 BTUs per ton-mile of cargo. An alternative approach is to assume that these combination aircraft exist primarily for passenger service, with freight carried only on a space available basis. The bulk of the fuel use is then allocated to passenger service on the assumption that the plane would not be scheduled without passengers, so that freight need only be responsible for the marginal or incremental energy needed to move its weight. A typical estimate is about 3,300 BTUs per ton-mile of cargo. Of the two approaches, the last is preferable since it appears to correspond most closely with airline priorities. 12/ The growth in passenger load factors under deregulation shows that airlines favor passengers at the expense of freight. Also, in the last few years, the air freight industry appears to have made more use of all-freight aircraft because of the better service they provide.

Overall air freight energy intensity can be estimated by combining energy for all freighter aircraft and for combination aircraft. Using the incremental approach for combination aircraft, a typical overall estimate is 12-14,000 BTUs per ton-mile of cargo.

Pipelines

Table A-6 presents estimates of the propulsion energy requirements for pipelines. In general, petroleum pipelines are one of the most energy-efficient modes of transportation.

As with other modes, there is considerable variation depending on the commodity moved, the speed and conditions under which it is being moved (most obviously, uphill or downhill), and the size of the pipeline. Table A-6 indicates that natural gas requires about six times as much energy per ton-

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12/ This is also the conclusion reached by Rose after a careful review of existing data.

TABLE A-6. ESTIMATES OF PROPULSION ENERGY REQUIREMENTS FOR PIPELINES

Source a/	BTUs per Ton-Mile b/	Comments
Hooker	270	Crude petroleum
	320	Petroleum products, natural gas
W. F. Banks	286	1976, crude petroleum
	330	1976, oil
	388	1976, petroleum products
	2,000	1974, natural gas
Leilich	158	1972, regulated pipelines only
	281	1980, projected, regulated pipelines only
CACI	475	1975, estimated
	411	1975, estimated for crude petroleum
	537	1975, estimated for petroleum products
DelCan	752	1976, Canada
Hooker and Others	283	Petroleum products, estimates
	326	for two separate companies

a/ See Appendix B for full citation of each source.

b/ Per ton-mile of cargo unless stated otherwise.

mile of load as most petroleum products since gas is much less dense than oil. Gas pipelines are also more energy-intensive, using about 2.5 percent of the energy transported or five to six times as much as for oil or oil-product pipelines. 13/ A small pipeline (say 4 inches in diameter) requires about

13/ J. N. Hooker, Oak Ridge National Laboratory, Oil Pipeline Energy Consumption and Efficiency, prepared for the U.S. Department of Energy.

eight times as much energy per ton-mile to move crude oil as does a very large one (say 48 inches in diameter). 14/

Most of the estimates in Table A-6 are based on aggregate data. Hooker and others, however, give data for two separate firms, with the larger of the two reporting lower energy requirements (283 BTUs per ton-mile of cargo).

Coal Slurry Pipelines

Slurry pipelines represent a relatively new technology in which solid material, such as coal, is ground into a powder, mixed in solution with a liquid such as water, and pumped through a pipeline. While many combinations of materials are possible, coal/water slurries currently receive the greatest attention. One coal/water slurry pipeline is now in operation moving coal from Black Mesa, Arizona, to a power plant at Mohave, Nevada. There are several active proposals to build other large pipelines mostly in the West.

Table A-7 presents several estimates of energy requirements for coal/water slurry pipelines. The first four sets of estimates are based on analyses of the Black Mesa pipeline, while the last two represent engineering-based analyses of proposed pipelines.

Coal slurry pipelines require energy at several distinct stages: collection (via pumps and pipelines) of the required water; preparation of the slurry (pulverizing the coal and mixing it with the water); pumping of the slurry; dewatering or separating of the coal and water at the end of the pipeline; and finally, disposal of the dirty water. The estimates for energy use by the Black Mesa line vary quite widely, from about 300 BTUs per ton-mile of load to over 4,000. The lowest estimate is clearly faulty since it excludes the energy used in generating electricity; because of thermal losses, generation requires about three times the energy content of the electricity itself. Even after correcting for this factor, the range of estimates for the energy requirements of this facility is surprisingly wide. Some of the variation may be the result of failure to consider all the energy

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14/ J.N. Hooker, Oil Pipeline Energy Consumption and Efficiency. The average velocity is another very important factor, with energy requirements increasing in proportion to velocity raised to the power of 1.852. See Leilich and others, pp. 3-49, 3-50.